LOAD CARRIAGE INDUCED ALTERATIONS OF PULMONARY FUNCTION

BY

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Abbreviated Title: PULMONARY FUNCTION DURING LOAD CARRIAGE

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

A186 227

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution is unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION: U.S. Army Res Inst of Env Med	6b. OFFICE SYMBOL (If applicable): SGRD-UE-MEP
7a. NAME OF MONITORING ORGANIZATION: U.S. Army Research Institute of Environmental Medicine	
6c. ADDRESS (City, State, and ZIP Code): Kansas St. Natick, MA 01760-5007	7b. ADDRESS (City, State, and ZIP Code): Kansas Street Natick, MA 01760-5007
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: Same as 6.a.	8b. OFFICE SYMBOL (If applicable)
9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
	3E162777 A879	879/BD	127

11. TITLE (Include Security Classification)
(U) Load Carriage Induced Alterations of Pulmonary Function

12. PERSONAL AUTHOR(S)
S.R. Muza, W.A. Latzka, Y. Epstein and K.B. Pandolf

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Manuscript	FROM ______ TO ______	May 1987	17

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Load Carrying, Pulmonary Function

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

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20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: XX UNCLASSIFIED/UNLIMITED X SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED	
22a. NAME OF RESPONSIBLE INDIVIDUAL: CPT Stephen R. Muza, Ph.D.	22b. TELEPHONE (Include Area Code): 617-651-4834	22c. OFFICE SYMBOL: SGRD-UE-MEP

DD Form 1473, JUN 86 — Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

Unclassified

19. Abstract (cont'd)

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ABSTRACT

Load carriage systems supported by the trunk have been shown to decrease certain indices of pulmonary function. We investigated the hypothesis that these pulmonary function reductions are directly related to the backpack load carried due to the mechanical constraint it imposes on the thoracic cage. To investigate this hypothesis, 5 young males with no pulmonary disorders were tested while standing upright carrying well-fitted 0, 10 or 30 kg loaded U.S. Army ALICE backpacks. Forced vital capacity (FVC), forced expiratory volume (FEV_1) and 15 s maximal voluntary ventilation (MVV_{15}) were measured. With increasing load, FVC and FEV_1 progressively decreased reaching 6 and 6.7% decrements ($p<0.05$) respectively with the 30 kg load. The MVV_{15} was decreased ($p<0.05$) by about 8.4% with the 10 kg load, but did not demonstrate any further decrement with the 30 kg load. Analysis of flow-volume loops obtained with the 0 and 30 kg loads showed that the reduction of FVC was not associated with any decrement of peak inspiratory or expiratory flows. These results indicate a limitation on the ventilatory pump caused by load carriage which is directly related to the load carried and characteristic of restrictive diseases of the respiratory system (reduced FVC and FEV_1 with no decrement in $FEV_1 \cdot FVC^{-1}$).

Keywords: Load Carrying, Pulmonary Function.

1. Introduction

It is generally accepted that the respiratory system does not limit exercise in normal subjects but may limit exercise in patients with lung disease (Bye et al. 1983). The respiratory pump may fail to provide sufficient ventilation to prevent arterial hypoxemia if its displacement is restricted or the respiratory muscles cannot generate sufficient force to displace the chest wall.

In a study by Legg and Mahanty (1985) comparing five modes of carrying a load close to the trunk, the subjects reported difficulty breathing while carrying a load equal to 35% of the subject's body weight. During the walk, the average oxygen uptake and minute ventilation were 1.15 $L \cdot min^{-1}$ and 32.5 $L \cdot min^{-1}$ respectively representing light work. Overall, the five load carriage systems reduced forced vital capacity (FVC) and forced expiratory volume in 1s (FEV_1) by approximately 7% each and 15s maximal voluntary ventilation (MVV_{15}) by about 13%. These results indicate a limitation on the ventilatory pump caused by load carriage which is characteristic of restrictive diseases of the respiratory system (reduced FVC and FEV_1 with no change in $FEV_1 \cdot FVC^{-1}$). We were interested in determining whether these load carriage induced decrements of pulmonary function are dependent upon the size of the load carried. Therefore, the present study assessed the pulmonary function responses to carrying various loads in a backpack.

2. Methods

2.1. Subjects

Five male soldiers volunteered to participate in the study. They received a physical examination and were informed of the purpose and procedures of the study, any known risks and their right to terminate participation at will without penalty. Each expressed understanding by signing a statement of informed consent.

*****TABLE 1 HERE****

2.2. Physiological Measurements

Measurements of FVC and FEV_1 were obtained using a wet seal bell spirometer (Collins 9 L Respirometer). The subjects were instructed to inspire maximally to total lung capacity (TLC), then to exhale as forcefully, rapidly and as completely as possible to residual volume (RV). All tests were conducted in triplicate with the best effort recorded. Measurement of FVC and FEV_1 and calculation of $FEV_1 \cdot FVC^{-1}$ were done using standard methods (West 1982). The MVV_{15} was determined using a nonrebreathing circuit connected to a low resistance dry gas meter (Singer, DTM-325). The subjects were instructed to breathe as hard and as fast as possible for 15 s. The minute ventilation was calculated by multiplying the total volume expired by four. All lung volumes were corrected to BTPS.

In several subjects, flow-volume curves were obtained using a pneumotachograph (Hewlett Packard, model 47304A) placed in line with the mouthpiece and inspiratory hose of the spirometer. The calibration of the pneumotachograph was checked using a factory calibrated flow meter (Fischer & Porter). The inspiratory and expiratory flows were integrated to give inspiratory and expiratory volume respectively. The volumes determined by integration of flow were compared with the volumes simultaneously measured by spirometry to ensure their accuracy. The subjects performed maximal inspiratory and expiratory efforts from RV and TLC respectively.

2.3. Experimental Design

All tests were conducted with the subjects wearing the U.S. Army Battle Dress Uniform. The subjects stood at rest while wearing, 1) no backpack, 0 load, 2) an All-Purpose Lightweight Individual Carrying Equipment (ALICE) pack frame weighing 10 kg and 3) an ALICE pack frame weighing 30 kg. Lead bars strapped to the cargo shelf of each ALICE pack frame were used to increase the load carried. Each subject performed the pulmonary function tests under each of the three conditions in a balanced randomised sequence. The subjects were given at least 30 s rest between forced expiration tests and 30 min between MVV_{15} tests. Two subjects performed flow-volume loop tests on a separate day. Only the 0 load and 30 kg load conditions were used during the flow-volume loop tests.

2.4. Statistical Treatment

An analysis of variance (ANOVA) was used to statistically compare the ventilatory responses obtained during the three load carriage conditions. In the event that the repeated measures ANOVA revealed significant ($p<0.05$) effects, Tukey's critical difference was calculated and used to locate significant differences between means.

3. Results

Table 1 summarizes the physical characteristics of the test subjects. As a group, the subjects demonstrated normal pulmonary function when compared to predicted values for these measurements (Boren et al. 1966). During the control (0 load) tests, none of the subjects reported any discomfort performing these maximal effort ventilatory maneuvers. However, when wearing the loaded backpacks, during maximal inspirations all subjects indicated the sensation of chest wall (rib cage and abdomen) restriction.

****FIGURE 1 HERE****

Values of the group mean FVC obtained with the 3 load conditions are shown in figure 1. FVC was decreased as load increased. The decrement was not statistically significant ($p>0.05$) with the 10 kg load but was significant ($p<0.05$) with the 30 kg load when compared to the 0 or 10 kg loads. The reductions were approximately proportional to the magnitude of the load. Wearing the 10 and 30 kg backpacks reduced FVC from its baseline value (0 kg load) by 2.5 and 6% respectively.

****FIGURE 2 HERE****

The FEV_1 was also found to be reduced in approximate proportion with the backpack load (figure 2). The FEV_1 was significantly ($p<0.05$) decreased by both the 10 and 30 kg loads when compared to the 0 load or each other. The FEV_1 was reduced by 3 and 6.7% from control by use of the 10 and 30 kg backpacks respectively. Given that both the FVC and FEV_1 demonstrated decrements roughly proportional to the load carried in the backpack, it followed that the ratio of $FEV_1 \cdot FVC^{-1}$ was not altered by increasing backpack load. This is shown in figure 3 where the $FEV_1 \cdot FVC$ ratios were 82.8 ± 3.3, 82.0 ± 3.4 and 82.1 ± 3.6 for the 0, 10 and 30 kg loads respectively.

****FIGURE 3 HERE****

To further examine how the backpack altered the generation of maximal, voluntary vital capacity and flow maneuvers, flow-volume loops were measured in several subjects. Each flow-volume loop was generated by the subject first exhaling to RV then immediately performing a maximal inspiratory effort to TLC followed by a maximal expiratory effort back to RV. In figure 4 is shown one subject's flow-volume loops obtained with the 0 and 30 kg loads.

****FIGURE 4 HERE****

Comparison of the flow-volume loops obtained with the 0 and 30 kg loads showed the same decrement in FVC as previously measured with the spirometer. Furthermore, analysis of the loops demonstrated that the reduction of FVC was not associated with any decrement of peak inspiratory or expiratory flows. Likewise, at intermediate and low lung volumes the effort-independent portion of the expiratory flow-volume curves were not altered by wearing the 30 kg backpack.

The results of the maximal voluntary ventilation tests are presented in figure 5. The MVV_{15} was significantly ($p<0.05$) reduced wearing the 10 and 30 kg backpacks as compared to control. However, unlike the FVC and FEV_1 responses, the MVV_{15} was similar for both the 10 and 30 kg backpack loads. The MVV_{15} was reduced by 8.4 and 9.5% from control by use of the 10 and 30 kg backpacks respectively.

****FIGURE 5 HERE****

4. Discussion

We examined the effect that wearing a load carriage system has on pulmonary function. Our results indicate that several indices of pulmonary function are reduced in rough proportion to the load carried. With increasing backpack load, the FVC, FEV_1 and MVV_{15} were reduced. Over the range of loads examined, there appears to be a linear decrease of FVC and FEV_1 with increasing backpack load, whereas the MVV_{15} demonstrates a decrease by addition of a small load and no further decrement with increasing load.

It seems reasonable to expect that since many load carriage systems are most metabolically efficient when carried on the trunk (Datta and Ramanathan 1971), these systems may alter pulmonary ventilation by interfering with movement of the chest wall. While numerous studies have investigated the effect of carrying loads on energy expenditure (Goldman and Iampietro 1962, Legg and Mahanty 1985, Pimental and Pandolf 1979), walking patterns (Martin 1986) and perception of exertion (Goslin and Rorke 1986), only one previous study has examined alterations in pulmonary function (Legg and Mahanty 1985). Legg and Mahanty (1985) reported that with five different load carriage systems carrying a load equal to 35% of the subject's body weight reduced FVC, FEV_1 and MVV_{15}. Our results with the 30 kg loaded backpack are similar to the findings of Legg and Mahanty (1985) using a similar backpack and frame. Their average reductions in FVC and FEV_1 were both about 5% whereas ours were about 7%. This difference is reasonable since our 30 kg load was about 42% of our subjects' body weight compared to their test load equal to 35% of body weight.

Legg and Mahanty (1985) found that the magnitude of the reductions were related to the style of load carriage system used. Generally, the greatest decrements in pulmonary function were associated with load carriage systems which covered the entire trunk (jacket, combination front and back packs). The standard military backpack with tubular metal frame produced the smallest decreases in pulmonary function. We chose the U.S. Army ALICE backpack and frame for testing because of its wide use in the army and the large range of loads which it is employed to carry. Given the results obtained by Legg and Mahanty (1985), our use of this style of load carriage system probably minimised the decrements in pulmonary function which we observed as a function of the load carried. Many U.S. Army special operations teams use internal frame or frameless rucksacks which have been shown (Legg and Mahanty 1985) to cause greater pulmonary function decrements. Members of a Special Forces Team using an internal frame pack weighing about 45 kg with sternum strap have reported difficulty breathing due to chest restriction (personal communication). Taken together, the results of our study and the previous report by Legg and Mahanty (1985) indicate that the degree of pulmonary function decrement incurred by backpack wear is dependent upon both the load and the style of carriage system used.

The ventilatory system consists of the lungs, rib cage, diaphragm and abdomen, including the abdominal wall. The latter three components are called the chest wall. During normal, unloaded, resting breathing, the respiratory muscles are at rest at the end of expiration. The volume of air in the lungs at the end of a normal, relaxed expiration is referred to as the Relaxation Volume (V_{rel}). The lung volume occupied by the V_{rel} changes with posture and is determined by the establishment of an equilibrium between the elastic recoil of the lung, directed inward, and the elastic recoil of the chest wall, directed outward. The V_{rel} is composed of two lung volumes, the residual volume (RV) and the expiratory reserve volume (ERV). Wear of load carriage systems on the trunk probably decreases the V_{rel} by opposing the outward elastic recoil of the chest wall. It is obvious that use of a hip belt compresses the abdominal contents thus pushing the diaphragm upward into the thoracic cage and decreasing the ERV. The decreased V_{rel} may contribute to a sense of chest wall constriction even when the subject is between inspirations. Our results and others (Legg and Mahanty 1985) indicate that use of load carriage systems decreases the vital capacity (VC). The VC, which changes with posture (Appel et al. 1986), is equal to the total lung capacity (TLC) minus the RV. It is obvious that the RV would not be increased by wear of a backpack. Given that when carrying loads the subjects reported feelings of chest wall restriction, it would appear that the decrease of VC is due to a decrease of the TLC.

Use of load carriage systems on the trunk may oppose breathing in a manner similar to elastic loads. The pressure produced by an elastic load is directly related to the volume inspired. It is likely that while wearing a backpack, greater forces must be generated by the respiratory muscles during inspiration in order to overcome the forces produced by the load carriage system. Agostoni et al. (1978) have shown that in resting, conscious subjects respiratory frequency usually increases and the tidal volume decreases with elastic loading. These changes in the pattern of breathing may be the result of load compensating actions rising from intrinsic properties of the respiratory muscles, neural and chemical reflexes and behavioral components. At any given minute ventilation, wearing a backpack probably increases the work of breathing. Consequently, greater respiratory central drive and muscle tension must be developed to achieve a ventilatory rate which meets the metabolic demands. Killian et al. (1984) have reported that the sensation of breathlessness and effort are psychophysically the same. If so, then the use of load carriage systems may elicit unpleasant respiratory sensations as reported by Legg and Mahanty's (1985) subjects during moderate exercise. Whether the use of load carriage systems on the trunk could cause the development of respiratory muscle fatigue or in the absence of fatigue unpleasant respiratory sensations which limit work performance is yet to be determined. Finally, in many industrial and military tasks the combination of respiratory protective mask wear with backpack use may impose work performance limitations associated with the development of respiratory muscle fatigue or dyspnea.

The current study and the investigation by Legg and Mahanty(1985) report decrements of MVV_{15} which are further evidence that wear of load carriage systems alter the pattern of breathing at least during high levels of ventilation. During the performance of the MVV_{15}, normal subjects with unopposed ventilation generally use a tidal volume of about 30% of VC with equal inspiratory and expiratory durations (Mead and Agostoni 1964). Given that the wear of a backpack reduced FVC by about 7%, the tidal volumes achieved during the MVV_{15} maneuvers should not have been limited by the decrease of FVC. Likewise, the flow-volume loops with and without the backpack did not indicate a decrease in the ability to develop maximal inspiratory and expiratory air flows. However, if the MVV maneuver was forced to be done at a lower lung volume where lower maximal expiratory flows were available, then a decreased MVV would be expected. Without analysis of the pattern of breathing during the MVV_{15} maneuvers, the changes in volume or timing which resulted in the decreased MVV_{15} cannot be determined.

Decreases in vital capacity and maximum flow rate are criteria for restrictive diseases of the respiratory system. Furthermore, inspiration is limited by the reduced compliance of the lung or chest wall, or weakness of the inspiratory muscles (West 1982). Use of load carriage systems on the trunk produces some of the pulmonary dysfunctions seen in restrictive respiratory diseases. However, most restrictive diseases involve changes in the interstitium which disrupts alveolar-capillary gas exchange as well as respiratory mechanics (West 1982). Consequently, patients with interstitial lung disease developed arterial hypoxemia during exercise despite normal minute ventilations (Lourenco et al. 1965). However, the use of load carriage systems may limit exercise only if sufficient ventilation cannot be achieved or maintained to prevent arterial oxygen desaturation or dyspnea from hypercapnia. Further studies need to determine the effect carrying a backpack has on the pattern and mechanics of breathing during rest and sustained aerobic exercise.

Acknowledgements

The authors express their appreciation to the volunteers whose participation made this study possible. The authors gratefully acknowledge Robert Hesslink for his technical assistance, Tammy Doherty for her statistical analyses and Dr. Michael Sawka and Dr. David Leith for their constructive criticisms.

The views, opinions and/or findings in this report are those of the authors and should not be construed as official department of the Army position, policy or decision unless so designated by other official documentation. Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research.

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Figure Legends

Figure 1. FVC (BTPS) response to added backpack load. Group mean (±S.E.) is plotted, * indicates significant ($p<0.05$) difference.

Figure 2. FEV_1 (BTPS) response to added backpack load. Group mean (±S.E.) is plotted, * indicates significant ($p<0.05$) difference.

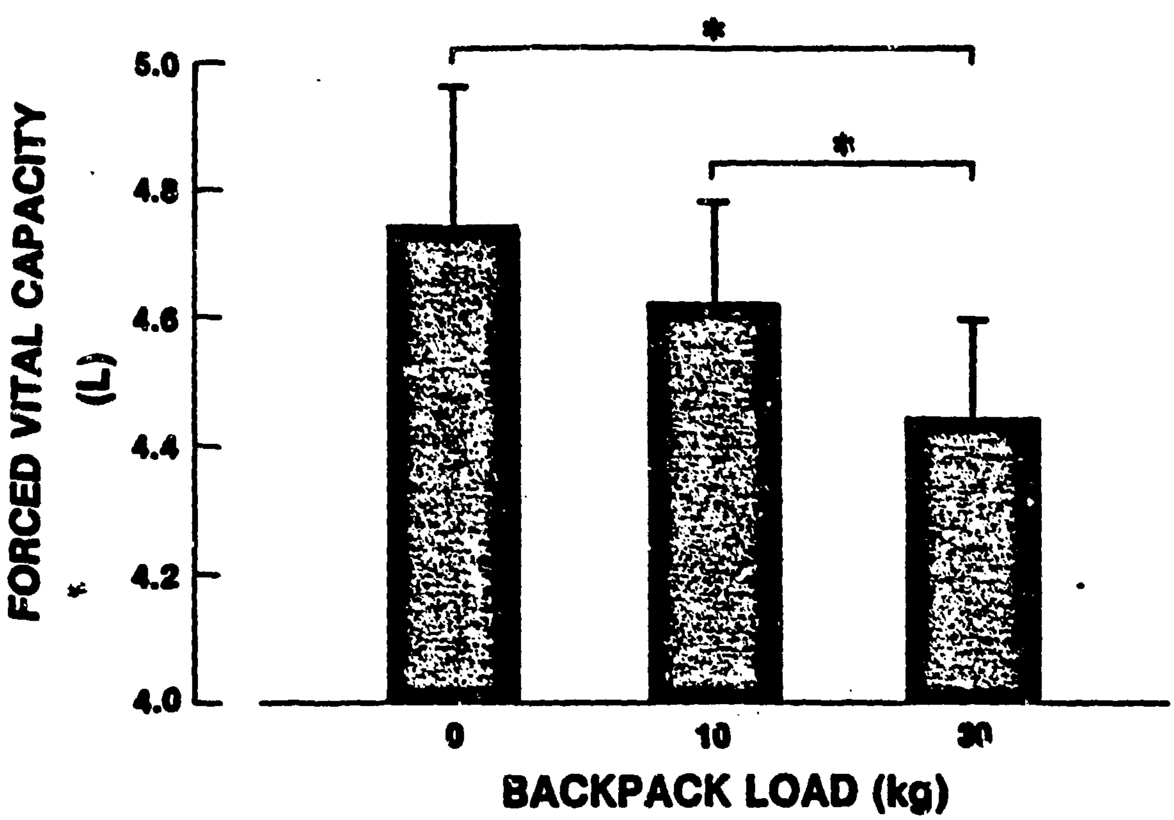
Figure 3. $FEV_1 \cdot FVC^{-1}$ response to added backpack load.

Figure 4. Flow-volume loops (BTPS) during maximal voluntary inspiratory (- flow) and expiratory (+ flow) efforts. Solid line is test with 0 load, dotted line is with 30 kg load.

Figure 5. MVV_{15} (BTPS) response to added backpack load. Group mean (±S.E.) is plotted, * indicates significant ($p<0.05$) difference.

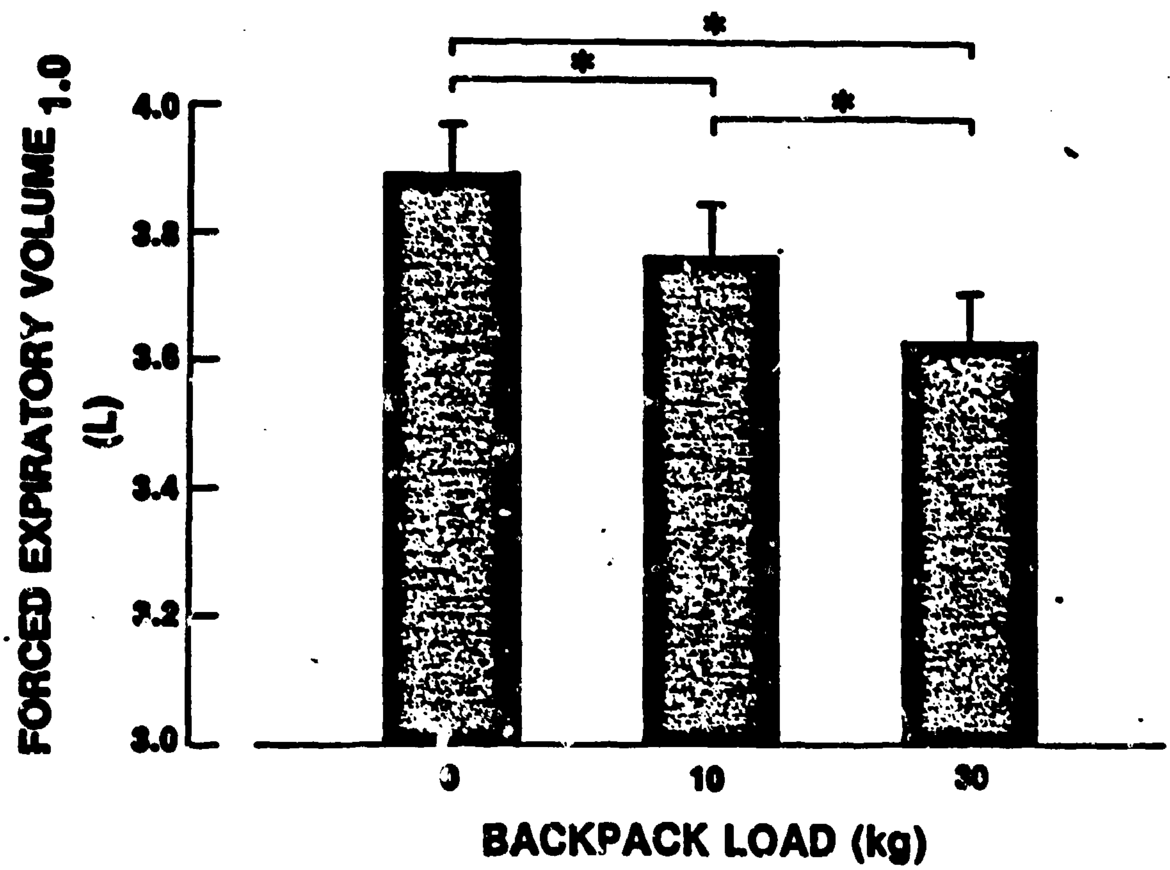
Table 1. Physical Characteristics of the Subjects

SUBJECT #	AGE y	WEIGHT kg	HEIGHT cm	FVC	$FEV_{1.0}$	MVV
				% predicted		
1	25	62.5	165.5	111.6	102.9	119.2
2	19	72.9	180.5	95.3	90.0	77.6
3	19	72.6	175.5	95.4	88.0	90.0
4	19	77.8	183.0	69.8	84.5	86.1
5	19	68.7	171.5	93.2	96.3	110.7
MEAN	20	70.9	175.2	93.1	92.3	96.7
(±SE)	(1.2)	(2.5)	(3.1)	(6.7)	(3.3)	(7.8)



FORCED VITAL CAPACITY
(L)
5.0
4.8
4.6
4.4
4.2
4.0
*
*
0
10
30
BACKPACK LOAD (kg)

Fig 1



FORCED EXPIRATORY VOLUME 1.0
(L)
4.0
3.8
3.6
3.4
3.2
3.0
*
*
*
0
10
30
BACKPACK LOAD (kg)

Fig. 2

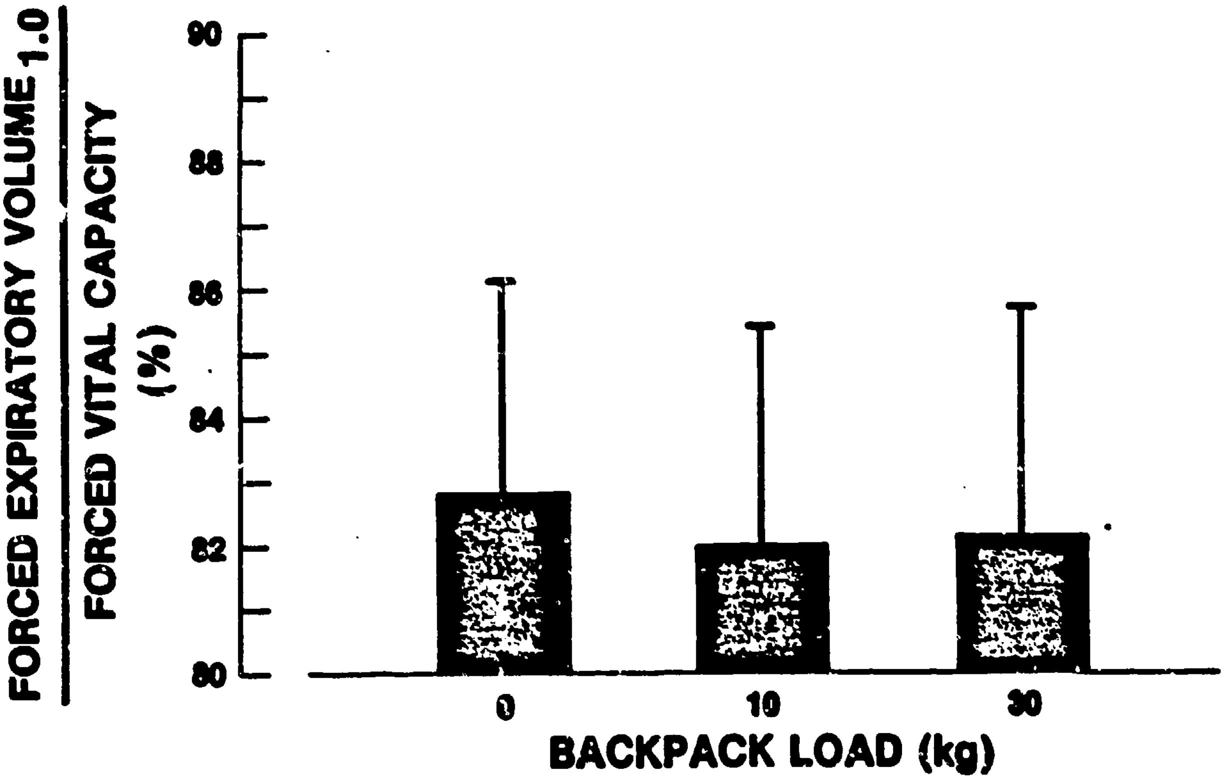

FORCED EXPIRATORY VOLUME 1.0
FORCED VITAL CAPACITY
(%)
90
88
86
84
82
80
0
10
30
BACKPACK LOAD (kg)

Fig 3

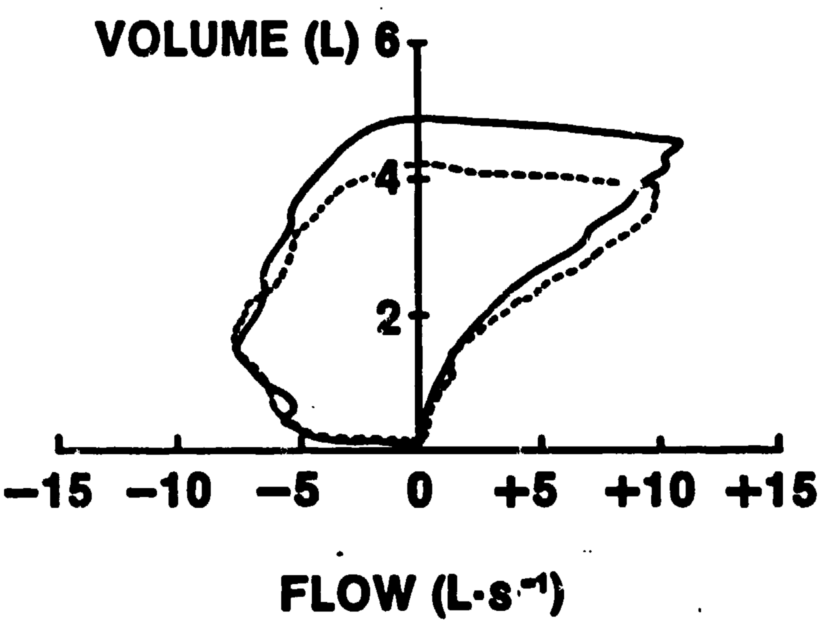


Fig 4

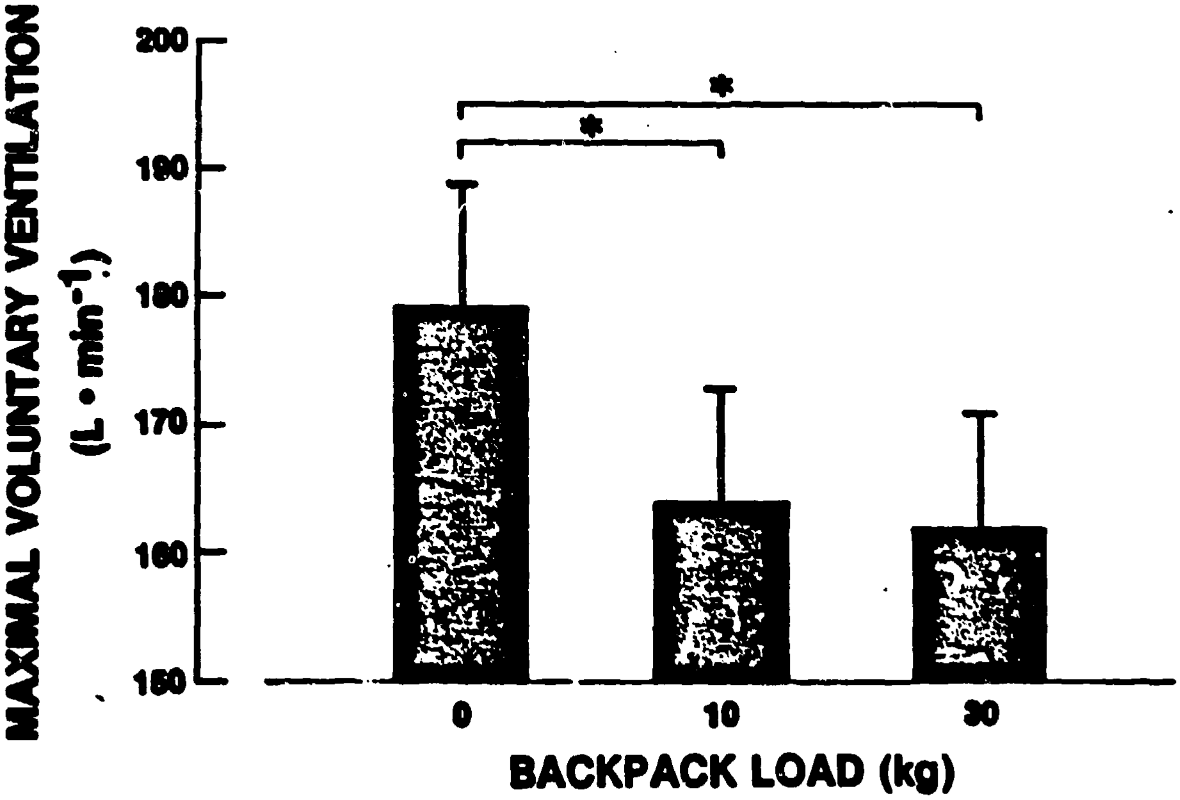

MAXIMAL VOLUNTARY VENTILATION
(L • min-1)
200
190
180
170
160
150
*
*
0
10
30
BACKPACK LOAD (kg)

Fig 5